

SPECTROSCOPIC IDENTIFICATION OF FAINT WHITE DWARF CANDIDATES IN THE PRAESEPE OPEN STAR CLUSTER

KURTIS A. WILLIAMS

Steward Observatory
 933 N. Cherry Ave, Tucson, AZ 85721

MICHAEL BOLTE

UCO/Lick Observatory
 University of California, Santa Cruz, CA 95064

AND

JAMES W. LIEBERT

Steward Observatory
 933 N. Cherry Ave., Tucson, AZ 85721

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ABSTRACT

We present spectroscopic observations of the remaining four candidate white dwarfs in Praesepe. All four candidates are quasars with redshifts between 0.8 and 2.8. One quasar, LB 6072, is observed to have a strong metal-line absorption system blueward of the quasar redshift. The lack of additional white dwarfs in Praesepe leaves the total known white-dwarf population of the cluster at five, well below the number expected from commonly-assumed initial mass functions, though several undiscovered cluster WDs may lie in the outer regions of the cluster. All known Praesepe member white dwarfs are concentrated within 0.6 of the cluster center, and the radial profile of cluster white dwarfs is quite similar to the profile of massive cluster stars. This profile is mildly inconsistent with that of $\sim 1M_{\odot}$ cluster stars and suggests that the white dwarfs did not receive a velocity kick during the progenitor star's mass loss phases. If complete, the observed Praesepe white dwarf population is consistent with a steeper high-end initial-mass function than commonly assumed, though the calculated slopes are inconsistent with the present-day mass function of Praesepe. Searches for white dwarfs outside the core of Praesepe and further study of the white dwarf populations of additional open clusters is necessary to constrain further the underlying cause of the white dwarf deficit.

Subject headings: white dwarfs — open clusters and associations: individual (Praesepe) — quasars: general — quasars: absorption lines — stars: luminosity function, mass function

1. INTRODUCTION

White dwarfs (WDs) are the final stage of stellar evolution for the vast majority of stars. WDs are known to exist in open clusters with main-sequence turnoff masses of $\sim 5M_{\odot}$ (e.g. NGC 2516, Koester & Reimers 1996) and may have progenitors with zero-age main sequence masses as large as $8M_{\odot}$. However, the WD population of the Hyades shows a deficit of WDs compared with the number that would be expected given the present-day mass function and reasonable assumptions for the shape of the initial-mass function (IMF) (Weidemann et al. 1992), and no Hyades WDs have inferred progenitor masses $\gtrsim 3.6M_{\odot}$ (Claver et al. 2001, hereafter CLBK01).

There are at least three explanations for this white dwarf deficit. First, the “missing” WDs may be hidden in unresolved binary star systems. A calculation of the number of hidden WDs finds that this can explain many, but not all, of the missing WDs (Williams 2004, hereafter W04). Second, dynamical evolution of the open cluster may remove WDs from the cluster (Weidemann et al. 1992). This effect is enhanced if the WDs receive a veloc-

ity “kick” during the mass-loss phase of the progenitor star (Fellhauer et al. 2003). Third, the higher-mass end of the initial-mass function (IMF) in the Hyades may have been steeper than commonly-observed IMFs, lacking stars with $M \gtrsim 4M_{\odot}$.

In part to address this issue, CLBK01 studied the WD population of the Praesepe open cluster. Praesepe has an age (~ 625 Myr) and metallicity ($Z = 0.024$) indistinguishable from that of the Hyades (CLBK01). Praesepe has a total mass of $\sim 600M_{\odot}$ and a half-mass radius ≈ 3.9 pc (Adams et al. 2002), more massive and more compact than the Hyades, which has a total mass $\sim 400M_{\odot}$ and a half-mass radius of ≈ 5.7 pc (Perryman et al. 1998), so losses of WDs due to dynamical evolution should be less in Praesepe than in the Hyades.

In Praesepe, CLBK01 found one WD with a massive progenitor, LB 1847 = EG 60, $M_i = 4.17M_{\odot}$, and four WDs with less-massive progenitors. Four other Praesepe WD candidates were not observed spectroscopically in that study due to their faintness; two of these (LB 1839 and LB 6072) have photometric properties consistent with cluster membership, a large WD mass and a progenitor mass $\gtrsim 5M_{\odot}$. If these objects are indeed cluster member WDs, they would be useful objects for exploring the value of M_{crit} and would mostly resolve the

Electronic address: kurtis@as.arizona.edu
 Electronic address: bolte@ucolick.org
 Electronic address: jliebert@as.arizona.edu

TABLE 1. OBSERVING LOG.

UT Date	Telescope	Object	Exp time (s)
08 Dec 2002	Keck	WD 0834+209	600
		LB 1839	600
12 Feb 2004	Keck	LB 6072	600
22 Mar 2004	Magellan	LB 6037	600

Praesepe WD deficit at these higher masses (W04).

As part of our ongoing study of open cluster WDs, we have obtained spectra of these four objects. §2 details the observations and spectroscopic identifications of each object, and §3 discusses the implications of this study.

2. OBSERVATIONS AND DATA REDUCTION

Spectra of Praesepe WD candidates were obtained between 2003 and 2004 with the Keck I 10m telescope and the Magellan Baade 6.5m telescope. An observing log is presented in Table 1. We note that the coordinates for LB 6037, LB 6072, LB 1839, and LB 1876 given in Table 3 of CLBK01 are labeled as J2000 coordinates, though the B1950 coordinates are published. For the sake of clarity, J2000 coordinates for all the objects in CLBK01 are given in Table 2.

The Keck observations used the upgraded blue camera of the LRIS spectrograph (Oke et al. 1995) with the 400 mm^{-1} , 3400Å blaze grism and a 1"-wide longslit at parallactic angle. The Magellan observation used the IMACS spectrograph with the f/2 camera, the 200 mm^{-1} , 6600Å blaze grism, and the 1"-wide slit in slit-viewing mode at parallactic angle. The resulting spectral resolution was 6Å for the Keck data and 7Å for the Magellan data. The spectra were reduced using standard NOAO *IRAF* routines. Relative flux calibration was obtained by applying the response function obtained from observations of spectrophotometric standards obtained on the corresponding observing run.

Spectra for each of the four remaining white-dwarf candidates are presented in Fig. 1. As can be seen, none of the four objects are WDs; all are QSOs. Redshifts for the QSOs were determined by cross-correlating the object spectrum with the SDSS composite QSO spectrum of Vanden Berk et al. (2001) using the *fxcor* package in *IRAF*. For illustrative purposes, an example of the cross-correlation values for LB 6072 are shown Fig. 2. The spectral identifications and redshifts of each object are summarized in Table 2. Each of these quasars is also assigned a QSO catalog designation (listed in the first column of the table).

Special difficulties were posed by LB 6037. The coordinates for this object in SIMBAD and CLBK01 are from Wagner et al. (1986); however, the object at these coordinates is not a blue object but a K star. In order to find any nearby blue objects, we blinked the blue and red second-generation Digitized Sky Survey plates from the ESO Online DSS server. A point source $\sim 1'$ west of the given coordinates stands out as being far bluer than anything else in the field. A spectrum of the blue source obtained at Magellan reveals it to be a QSO. We therefore identify this blue object as LB 6037 and give these coordinates in Table 2. A finding chart is pre-

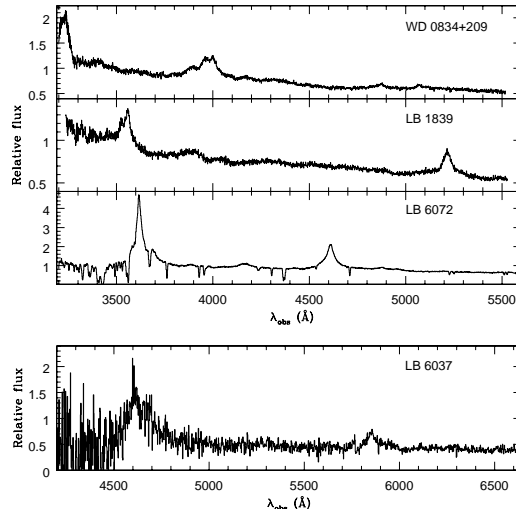


FIG. 1.— Spectra of the four candidate Praesepe white dwarfs. Spectra are unbinned and in (relative) units of f_λ .

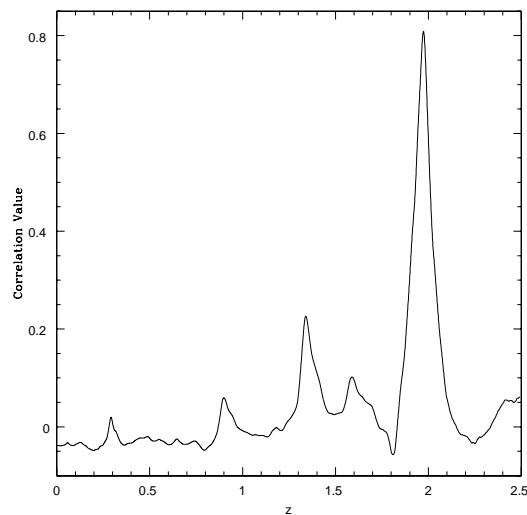


FIG. 2.— Correlation values for LB 6072. The correlation value as a function of redshift for cross-correlation of LB 6072 with the SDSS composite quasar spectrum from Vanden Berk et al. (2001). The sharp, high peak is the QSO redshift, $z = 1.975$.

sented in Fig. 3. Due to the lower signal-to-noise of this spectrum, the cross-correlation routine failed to converge satisfactorily. Manual line identifications give a redshift of $z = 2.78$.

LB 1839 was identified by CLBK01 as a proper motion member of Praesepe, though it is actually a QSO. As quasars have zero proper motion, this is an obvious error in the proper motion measurement. Measurements of “significant” proper motions for QSOs have been noted in a cross-correlation of the USNO-B and SDSS catalogs (Gould & Kollmeier 2004) and merely illustrate the difficulty in measuring small proper motions of faint objects.

3. DISCUSSION

3.1. Praesepe WD candidates and sample completeness

TABLE 2. SPECTROSCOPIC IDENTIFICATIONS

Object	Other Names	RA (J2000)	Dec (J2000)	V^a	$B-V^a$	ID	z^b
QSO J0837+2040	WD 0834+209 ^a	8 37 11.5	20 40 57.1	18.83	0.34	QSO	1.0916 ± 0.0013
QSO J0838+1933	LB 1839	8 38 37.2	19 33 13.2	18.83	0.23	QSO	0.8622 ± 0.0009
QSO J0843+1955	LB 6037	8 43 13.3	19 55 59	18.98	0.37	QSO	2.78 ± 0.01
QSO J0843+1937	LB 6072	8 43 45.7	19 37 24.2	18.73	0.24	QSO	1.9749 ± 0.0004^c
WD 0836+197	LB 5893	8 39 36.5	19 30 43.2	17.63	-0.06	WD	...
WD 0836+201	LB 393, EG 61	8 39 45.6	20 00 15.6	17.96	0.12	WD	...
WD 0836+199	LB 1847, EG 60	8 39 47.2	19 46 11.8	18.33	0.08	WD	...
WD 0837+199	LB 390, EG 59	8 40 28.1	19 43 34.4	17.60	0.04	WD	...
WD 0838+202	...	8 41 39.8	19 00 07.5	17.96	0.20	WD	...
WD 0840+200 ^d	LB 1876	8 42 52	19 51 12	17.69	0.15	WD	...

^aAs given in CLBK01, should not be used

^b 1σ errors calculated in *fxcor*

^cStrong metal absorption line system at $z = 1.82$

^dIncorrectly listed in CLBK01 Table 3 as “WD 0837+202”

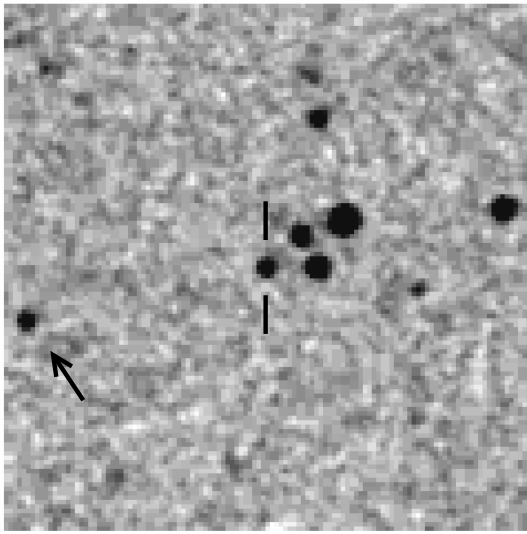


FIG. 3.— Finder chart for LB 6037, indicated by vertical tick marks. The arrow indicates a K star at the coordinates given for LB 6037 in Wagner et al. (1986). The image is a $2' \times 2'$ field taken from the blue plate of the second-generation Digitized Sky Survey.

Any conclusions about the Praesepe WD population will depend on the completeness of the WD candidate lists. CLBK01 do not discuss the completeness of their sample. They also included a few previously known WD candidates outside their survey area (outlined in Figure 4). However, the CLBK01 photometry is complete to $V \sim 19.5$, more than 1 mag fainter than the faintest Praesepe WD, so it is not unreasonable to assume that the sample is complete (aside from the complication of WDs in binary systems) in the central 2.1 square degrees ($\sim 50'$ radius) of Praesepe.

3.2. The Deficit of Praesepe WDs

Members of Praesepe are known to exist out to a radius of $\sim 8^\circ$ (Adams et al. 2002), so it is quite possible that more cluster WDs exist in the outer regions of the cluster, just as the WD population in the open cluster M67 is observed to extend to the largest cluster radii (Richer et al. 1998). The potential number of Praesepe WDs outside the surveyed area can be estimated by several means. Us-

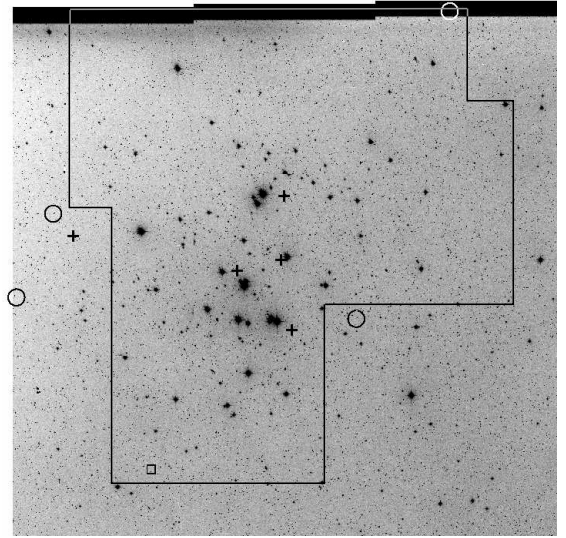


FIG. 4.— Mosaicked Digitized Sky Survey image of Praesepe. Crosses indicate locations of Praesepe WDs from CLBK01; the square indicates the CLBK01 non-Praesepe WD; open circles mark the location of the QSOs from this study. The outlined region represents the approximate coverage of CLBK01. The image is $\sim 2^\circ$ on a side.

ing the parameters of the best-fitting King model determined by Adams et al. (2002), we find that $\sim 85\%$ of the stellar content of Praesepe is outside the central $50'$. Using the profile of $\sim 1M_\odot$ stars in Raboud & Mermilliod (1998b), we estimate that $\sim 80\%$ of the stellar content is outside the surveyed regions. Therefore, *if* the WD population of Praesepe has the same radial distribution as that of the majority of the stellar population (discussed in §3.2), Praesepe may have a total population of ~ 25 to 30 WDs.

The number of expected, observable WDs in Praesepe was calculated in W04 to be seven to 21 WDs. This calculation used the luminosity function of Jones & Stauffer (1991), which covered the central ~ 16 sq. degrees of Praesepe. The large range in the number of expected WDs arises primarily from the assumed IMF. If this calculation is scaled by the radial profile of Raboud & Mermilliod (1998b) under the assumption that the WD radial profile follows that of the $\sim 1M_\odot$

stars, we estimate that ~ 1 to 5 WDs should be found in the central region studied by CLBK01, in agreement with the five known Praesepe WDs. If, however, these five known Praesepe WDs represent the *entire* WD population of the cluster, then Praesepe suffers from the same deficit of WDs as the Hyades (Weidemann et al. 1992).

WD Velocity Kicks

One explanation for the deficit of WDs in open clusters is that during the mass-loss phase of the progenitor star’s stellar evolution, the future WD is accelerated due to asymmetric mass loss, resulting in a small net velocity “kick” (Weidemann et al. 1992). A net velocity of just a few km/s is sufficient to remove the majority of WDs from an open cluster on short time scales (Fellhauer et al. 2003). In N-body simulations not considering velocity kicks, the WD populations of open clusters with ages similar to Praesepe have radial profiles very similar to those of the luminous stars and subgiants (Portegies Zwart et al. 2001; Baumgardt & Makino 2003).

Figure 4 shows the location of the five Praesepe WD candidates with respect to the cluster. The figure shows a $2^\circ \times 2^\circ$ region centered on Praesepe, which agrees well with the cluster core radius of $\sim 1^\circ$ (Adams et al. 2002). Also indicated on the figure is the region of sky studied by CLBK01. All of the cluster member WDs are located within $\sim 35'$ of the cluster center, even though the region studied in CLBK01 extends $\gtrsim 50'$ out from the center.

Figure 5a compares the cumulative distribution of WDs as a function of radius from the cluster center to the distribution of cluster stars interior to $50'$ from data by Raboud & Mermilliod (1998b). From the figure it appears that the WD distribution follows that of the massive cluster stars, exactly as predicted for a WD population with no net velocity kick. A K-S test comparing the WD radial distribution to that of the stars finds that the WD distribution is consistent with that of the stars with masses $\gtrsim 1.6M_\odot$ and weakly inconsistent with the distribution of lower mass stars.

To test further the significance of the WD radial distribution, two Monte Carlo simulations were performed. In the first, five stars were drawn from the central $50'$ radial distribution of the $\leq 1.2M_\odot$ stars in Raboud & Mermilliod (1998b). Out of 10,000 realizations, 13% had all five selected stars interior to the $35'$ extent of the known WD population. The second Monte Carlo simulation drew stars from the radial distribution of $M \leq 1.2M_\odot$ stars from the entire Raboud & Mermilliod (1998b) sample until five stars interior to $35'$ were found. Of these, only 15% of the realizations were found to have no additional stars in the annulus between $35'$ and $50'$.

These simulations hint that the WD population is more consistent with the giants and subgiants of Praesepe than with the lower mass, as-yet unevolved cluster members, as predicted by the N-body calculations that do not include a velocity kick. Figure 5b shows the resulting radial distribution of WDs compared with those for other Praesepe stars if the five known WDs represent the entire WD population of Praesepe. In this case, the similarity of the WDs with subgiant and giant Praesepe members is even more striking.

The concentration of WDs toward the center of the

cluster may not be inconsistent with the concept of velocity kicks if all the WDs with non-zero kicks have already been lost from the cluster (or are at larger radii). It would be useful for N-body simulations of open clusters to explore how the apparent radial distribution of WDs varies with the strength of the applied kick.

We also note that the Pleiad WD (LB 1497) is located ~ 1.4 away from the tightly-concentrated core of the cluster, well outside the half-mass radius ($\approx 53'$) but within the Pleiades tidal radius ($\approx 7.4'$) (Raboud & Mermilliod 1998a). This contrasts with the central concentration of WDs observed in Praesepe and further serves to muddy the waters.

Shape of the Initial-Mass Function

It is also possible that the dearth of WDs in Praesepe could be due to a steeper IMF than normally considered. To explore this possibility, we use the code from W04 to calculate the WD population of Praesepe for various IMF slopes. The parameters used to normalize the IMF and the WD detection criteria are the same as those for Praesepe presented in W04; M_{crit} is taken to be $8M_\odot$, and the binary fraction is taken to be 0.4. Two different IMFs were explored – a power-law IMF of the form $\xi(M) \propto M^{-(1+\Gamma)}$ and the broken power-law IMF from Naylor et al. (2002), with a steep high-mass power law IMF ($\Gamma = \Gamma_1$ for $M > 1M_\odot$) and a flat low-mass slope ($\Gamma = \Gamma_2 = 0.2$ for $M \leq 1M_\odot$).

The Praesepe member WD 0837+199 has a progenitor mass $\leq 4.17M_\odot$ (CLBK01). We therefore calculate the likelihood that, for a given IMF slope Γ , no WDs with progenitor masses $\geq 4.17M_\odot$ are observed. The value of Γ was then varied to find the slopes corresponding to confidence levels of 60%, 90%, and 95%. Results are given in Table 3. The calculations show that the lack of high-progenitor-mass WDs, the lack of WDs observed in binary systems, and the overall deficit of WDs in Praesepe can be explained by a steep high-mass IMF. Assuming Poisson statistics, both the $\Gamma = 2.55$ power-law IMF and the $\Gamma_1 = 2.75$ broken power-law IMF are remarkably consistent with the Praesepe WD population, though such steep IMFs are contrary to what is observed in younger open clusters (Kroupa 2002; Kroupa & Weidner 2003).

The present-day mass function (PDMF) of Praesepe has been discussed by several authors. Adams et al. (2002) find a PDMF slope of $\Gamma = 0.6$ for $1M_\odot \geq M \geq 0.4M_\odot$, somewhat shallower than the Salpeter slope of $\Gamma = 1.35$ and far shallower than the IMFs needed to explain the WD deficit. Williams, Rieke, & Stauffer (1995) find a steeper IMF for stars more massive than $0.6M_\odot$, with $\Gamma = 1.7$, though this is still shallower than the IMF required by our calculations.

3.3. Future work

In order to determine the significance of the observed WD deficit in Praesepe, and therefore determine the validity of the above discussion, it is necessary to conduct a search for Praesepe WDs out to larger radii. Including proper motions in such a study would be very helpful in reducing the large number of background and extragalactic objects. Unfortunately, existing proper motion surveys of Praesepe do not extend quite faint enough (e.g. Jones & Stauffer 1991).

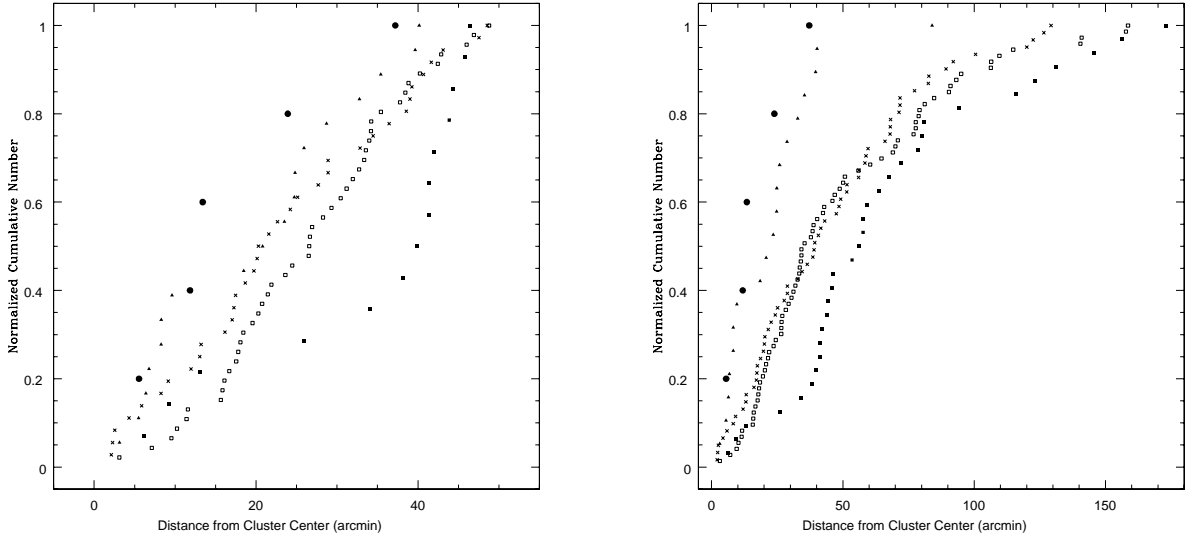


FIG. 5.— Radial distribution of stars and WDs in Praesepe (a) interior to $50'$ and (b) over the entire cluster. Large, filled circles show the cumulative radial profile of the five known WDs. The remaining data are taken from Raboud & Mermilliod (1998b), show the profile of stars with $M > 2.5M_{\odot}$ (triangles), $2.5M_{\odot} \geq M > 1.6M_{\odot}$ (crosses), $1.6M_{\odot} \geq M > 1M_{\odot}$ (open squares), $M \leq 1M_{\odot}$ (filled squares). The zero-age main-sequence masses of Praesepe giants are $\approx 2.7M_{\odot}$.

TABLE 3. CALCULATION OF THE PRAESEPE WD POPULATION

IMF ^a	Confidence	Γ	N_{WD}				
			Total	Observed	Observed in Binaries	Total ($M_i > 4.17M_{\odot}$)	Observed ($M_i > 4.17M_{\odot}$)
P	60%	2.55	5.7	4.1	1.6	1.9	0.95
P	90%	2.02	12.1	8.0	2.8	4.8	2.3
P	95%	1.87	15.0	9.7	3.3	6.2	3.0
N	60%	2.75	6.4	3.4	0.7	2.1	0.9
N	90%	2.16	13.6	7.2	1.3	5.1	2.3
N	95%	2.75	16.7	8.8	1.6	6.6	3.0

^aP= Power-Law IMF, N = Naylor et al. (2002) IMF

Examination of the complete WD content of additional clusters should be able to constrain these hypotheses even further. Comparison of the WD populations of similar-age clusters of varying total masses can determine the degree of any dynamical contributions to the WD deficit, as more massive clusters should retain a larger fraction of WDs if dynamical effects dominate the WD deficit. Examination of young stellar clusters with masses similar to Praesepe and the Hyades may help to constrain the high-mass IMFs, especially if a steep IMF is observed in these clusters.

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veys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. Some of the data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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